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EVALUATE THE APPLICATION OF MODAL TEST AND ANALYSIS  
PROCESSES TO STRUCTURAL FAULT DETECTION IN  
MSFC - STS PROJECT ELEMENTS

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## ABSTRACT

The Space Transportation System (STS) is a very complex and expensive flight system which is intended to carry very unique payloads into low earth orbit and return. A catastrophic failure of the STS (such as experienced in the 51-L incident) results in the loss of both human life as well as very expensive and unique hardware. One impact of this incident has been to re-affirm the need to do everything possible to insure the integrity and reliability of the STS is sufficient to produce a safe flight.

One means of achieving this goal is to expand the number of inspection technologies available for use on the STS. The purpose of the activity reported here was to begin to evaluate the possible use of modal analysis and test techniques for the purpose of assessing the structural integrity of STS components for which Marshall Space Flight Center (MSFC) has responsibility. This entailed reviewing the available literature and determining a low-level experimental program which could be carried out by MFSC and would help establish the feasibility of using this technology for structural fault detection.

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## INTRODUCTION

During recent years it has become increasingly necessary to assess the integrity of existing structural systems so as to determine their suitability for continued use. Examples of these structural systems include commercial and military aircraft, offshore oil platforms, commercial buildings in earthquake prone regions, and bridges. All of these examples are structures which represent a significant initial capital investment and/or the potential for harm to either human occupants or the environment or both if they fail.

Recently, the Space Transportation System (STS) has been added to this list. The STS has many components which are reuseable, and the Orbiter Vehicle is the most recognizable of these. In addition to the usual problems encountered in inspecting and evaluating the condition of a typical aerospace structure, the STS has several unique requirements which must be accommodated. These include exposure to an extremely hostile and wide ranging environment, the need to significantly reconfigure the vehicle for each flight, and a very tight schedule of access to the vehicle between flights.

The technology currently used to assess the integrity of the orbiter and other pieces of flight structure requires direct access to the areas to be inspected. Additionally, these technologies (such as ultrasonics, acoustic emissions, dye penetrants, and others) require the surface of the component to be inspected to be clean, and in many instances, the component must be physically removed from the structure. The result is an extremely localized inspection program which requires the expenditure of large amounts of time and labor, and can result in a degradation of the structural integrity just do to the disassembly-reassembly cycle involved. The DC-10 crash on take-off in Chicago a few years ago is a dramatic example of this possibility.

Less tragic but equally costly results can be produced by simple mistakes such as a bearing being improperly installed after an inspection of a large piece of equipment in the petrochemical or power generation industry. Therefore, any inspection scheme which either eliminates the need for or reduces the frequency of this type of detailed inspection process without sacrificing the quality of the inspection

can provide significant savings to the industry using it.

This approach has been used successfully in many process related industries and is referred to as "preventive maintenance". By monitoring such things as machine vibrations and the chemical composition of lubricants on a regular basis, it is possible to keep a running log of the condition of important pieces of equipment without removing them from service. In this manner, down-time and equipment outages can be controlled and scheduled to coincide with other related activities.

The purpose of the work performed under this program was to begin the evaluation of modal analysis methods for use as a structural fault detection tool. The major advantages this method has over those currently in use are that it is a global inspection technique, and does not require disassembly of the structure to be inspected. It may also be possible to extend the application of this technology to a point where it can function in a preventive maintenance role. However, the current interest in this technology centers around its global measurement capability, and the fact that it can be utilized without requiring any disassembly of the structure.

## PROJECT DESCRIPTION

As mentioned earlier, modal analysis and testing techniques have two major benefits to offer as a Non-Destructive Evaluation (NDE) method. These are 1) the global nature of the evaluation and 2) the fact that the evaluation can be performed without disassembling the structure. However, there are some significant questions which must be investigated before it will be possible to determine the extent of the usefulness of this method as an NDE tool.

These questions concern themselves with such things as the type of fixturing, if any, required, the amount and type of data to be taken, the accuracy and repeatability required for the data, the type of data processing to be used, the manner in which the data should be presented, the rationale for interpreting the data, and so forth. While this list is far from complete, it serves to illustrate the complexity of this issue.

Therefore, it was decided that the best approach to take in the present effort was to review the literature available on this topic, and then establish a low-level test program that could be carried out by the Dynamic Test Branch at MFSC. This test program would serve to familiarize their personnel with the use of modal test methods for NDE purposes, demonstrate the level of accuracy and repeatability which is needed, allow some preliminary evaluation of various data processing and presentation methods, and to generally illustrate how typical aerospace structural systems will behave when damage is present. The results of these preliminary investigations will provide the basic information required to determine how best to proceed with a more advanced and ambitious evaluation program.

### Literature Survey

The fact that the frequency content of a vibrating system changes as the physical characteristics of the system change has been used to advantage in several areas. These range from the above mentioned application to preventive maintenance and troubleshooting as described by Downham and Woods [5], Glew and Watson [6], Cempel [82], and Mutch and Russell [86] to the determination of the elastic properties of structural adhesives as explained by Adams and Crippendale [81].

One does not have to expend much effort to discover that this concept has been applied in many different forms to many different problems. This is demonstrated by the set of references listed at the end of this report. While this list is by no means complete, it does serve to illustrate the point quite well. In particular, these articles can be divided into several general categories, and they will be described in this manner.

Two areas which have received considerable attention in recent years are civil engineering structures and offshore oil platforms. Yao and his colleagues [11,15,16,78-80] have published extensively on the subject of inspecting civil engineering structures. The goal being to define a method of assessing the integrity of these structures after their exposure to some situation such as an earthquake which could severely damage a structure without causing it to collapse. The outcome of this work has been a probabilistic method to quantify the damage as either minor or moderate or severe coupled with an attempt to computerize the evaluation process. Inputs range from subjective evaluations made by inspectors to actual empirical data. There is no indication of how successfully the system works.

Krauthammer [9] has suggested a numerical evaluation plan similar in intent to that of Yao. Matzen and Hardee [10] have demonstrated a numerical method based on the Hessian matrix for determining if an element in an FEM model has a value of stiffness equal to zero. The ability of the method to determine a value other than zero was not studied. Sparks, Jeary and de Souza [17] are but one set of investigators that have examined the use of ambient excitation to determine the dynamic properties of a building. Kopff [21] has attempted to set down a rationale for inspecting large natural convection cooling towers also using ambient excitation. All of these investigations are lacking both experimental verification and a method of correlating the presence of damage to changes in dynamic properties.

Another type of structure which has received a fair amount of attention is the offshore oil platform. This class of structure is both unique and extremely expensive. Also, a sudden failure of such a structure can have a tremendous impact on the environment as well as the potential loss of human life. The two main obstacles faced by investigators in this area are both related to economics. The first is the general need to find an answer quickly when structural damage is suspected coupled with the lack of interest on the part of the petroleum industry in supporting fundamental

research on this topic. The second is the fact that the platform cannot be casually taken out of service at any time during its life. The cost of putting these structures into service and then keeping them operating is enormous. Therefore, any NDE which must be performed on these structures must take place while the platform is operating. This can complicate the measurement and analysis process to the point where it is virtually fruitless.

Loland, Mackenzie, Begg and Bendat [8,14,19] have highlighted some of these difficulties. One of the most significant of these is determining an adequate model of the platform which can be used with modal analysis procedures to determine structural integrity. This is not a simple problem. Kummer, Yang and Dagalakakis [13] have applied the "log decrement" technique to simple structures to detect the presence of fatigue cracks with an eye to applying the results to offshore platforms. This application to real structures has yet to be accomplished. Vanduerzen, Leuridan and Doucet [28] have also applied modal analysis techniques to an offshore platform. Again, the model of the platform used was extremely simple and made it difficult to determine the precise condition of the structure.

Large rotating equipment has also received attention. The concern in these papers is the ability to avoid an unexpected catastrophic failure of these extremely large and expensive pieces of equipment. In addition, if the need to disassemble this equipment unnecessarily can be avoided, the financial benefits to the owner are significant. This concern results from the fact that the materials used in these large pieces of equipment are not, typically, very damage tolerant. Therefore, a relatively small crack can be devastating. References 59 to 63 and 67 describe several different variations of this problem. In all cases, no clear choice for an obvious monitoring scheme is identified.

There has also been much written in way of what can be termed general application of vibration analysis to damage detection or the detection of structural changes. The amount of published literature is extensive and References 20, 22, 23, 25-27, 29, 30, 43-58, 64-72, 84, 85 and 88 constitute a small but representative sample of the work in this area. Virtually all of this work concentrates on examining very simple structures or structural elements and, again, it is unclear whether this information can be applied to real structural systems.

There have also been a number of theses and dissertations written on this general subject, and References 31 to 41 are



reflective of this work. Of this body of work, only the contributions of Haisty [40] and Duerr [41] have addressed the need of providing the analyst as well as the experimentalist with the capability of evaluating the effect damage will have on the dynamic properties of a structure. In the long term, this will be an important feature of this technology. Again, none of this work has been applied to large structural systems.

One method which seems to be finding some favor is to force an FEM model to exhibit the measured structural vibration characteristics. Typically, this approach uses some type of optimization routine to determine the final configuration. Most of the work which falls into this category is either proprietary or else just developing. More of this work should be coming to publication in the near future.

#### Present Investigation

The need to monitor the structural integrity of aerospace structures is well established. The number of these systems in commercial service alone is staggering. Recent estimates put the number of departures and arrivals in excess of 26,000 per day. Each of these flights carries a large number of passengers and operates, at least a portion of the time, in areas of high population density. These facts all combine to produce a situation that would result in the loss of a large number of human lives if a catastrophic structural failure should occur.

In addition to this pressure, the military also has a tremendous inventory of aircraft of all types. While, in general, these aircraft carry fewer passengers and crew than those in civilian service, the sheer number of aircraft in the military inventory establishes an economic imperative, if nothing else, to keep them in the best possible health. However, it is not at all clear how the needed inspections should be accomplished. This situation is well documented by Sproat and Rowe [87]. They point out how the existence of all the competing inspection technologies complicate the issue even more. This reference details a four year test program carried out by Lockheed-Georgia for the Air Force which was intended to evaluate all of these competing methods. But, as stated earlier, everyone agrees that inspections are needed.

One approach to this problem has been to measure the strain experienced by the structural component or assembly of interest and use this data to make a determination of its integrity. An early attempt to implement this strategy is

documented by Bochniak and Garcia [42]. This report describes a twelve channel strain measurement and recording system which was developed for the Navy, and intended for use as an aircraft structural integrity monitoring device. There is no information concerning the success of the monitoring program.

A more recent attempt to accomplish the same goal is presented by Bruinsma et al. [3], and details the use of fiber-optic strain measurements to provide information concerning the structural integrity of composite materials. Again, this reference describes only the data acquisition strategy and no information is presented concerning an actual application of this device in a real system.

The investigation presented here resulted, in part, from the interest generated by a Level II Change Request and PRCBD #S40155 titled "Orbiter Structural Inspection Via Modal Processes." This request was initiated by Mr. Walter M. West Jr., JSC-ES4, as a possible solution to the problem of inspecting components of the shuttle which cannot practically be inspected using other technologies. The particular items of concern are control surfaces. These components are typically built-up structures and can sustain internal damage which cannot be detected by conventional NDE methods without removal of the component's aluminum skin.

The prime motivation for this concern resulted from an acoustic test of the body flap of the Space Shuttle. Cheng, Dunham and Joanides [83] have documented the basic test procedure and expected test results. After the completion of this evaluation program on the body flap, a modal survey revealed that some of its dynamic characteristics had changed. West determined that damage had accumulated in the body flap by reviewing the vibrational mode shapes.

Later, West [74-76] developed a technique for locating damage in structures using a modal vector correlation coefficient. The structure is partitioned into several components and the correlation coefficient between baseline and post-service mode shapes are calculated. For components in which no change has occurred, the correlation coefficient is near unity, while in damaged segments the value of the correlation coefficient is less than one. The procedure was applied to Space Shuttle test specimens with success.

Haisty, West and Mitchell [77] applied West's technique to the Space Shuttle Orbiter body flap test specimen with good results. Several damage sites were correctly identified using this technique which were not detected by conventional

NDE techniques. While this technique can locate damage in structures reasonably well, it is unable to determine the extent of the damage.

As an extension of these activities, work has recently begun at JSC to apply this technique to a small Cessna airframe. The goal is to inspect the control surfaces while they are installed in the airplane. The initial damaged placed in the structure will be used to evaluate the concept of using local modes (i.e. modes primarily attributed to the subsystem only) to detect damage in the control surfaces. While this work is still in progress, the preliminary results are favorable.

Further support for the use of modal analysis procedures as an NDE tool has been provided by the Structural Dynamics Research Corporation [73]. SDRC has reported cases in which damage in spacecraft and airplanes has been diagnosed as the result of routine modal tests. They conclude that modal analysis can be readily adapted to the identification of structural failures, that frequency response functions can quickly give an indication of whether or not damage has occurred in the structure, and the mode shapes can provide information about where the structural problem has occurred. This work also stops short of quantifying the damage present.

In addition to the work underway at JSC and the interest in evaluating this technology for use by MSFC-ET53, there are additional groups within NASA with similar problems. The first of these is MSFC-PD22. This group is working on development programs utilizing new materials which will have very unique properties. Because of this, it will be extremely important to have reliable, efficient, and economic NDE methods available for use on these systems. The propulsion group at MSFC also has interest in using measured quantities to determine the condition of the SSME and other related hardware. Many of the problems associated with these activities are similar, at least in form, to those reviewed in this report. Last, there is an apparent interest at the Langley Research Center in evaluating the application of modal analysis methods to the problem of assessing acoustic fatigue damage.

#### Existing Problems

The following problems currently exist and must be solved in order to make modal analysis an effective and useful NDE method:

1. Measurement noise.
2. Available excitation techniques for certain situations may limit the usefulness of the data.
3. Best methods for data presentation and processing are unclear.
4. Measurement accuracy and repeatability requirements are unknown.
5. Interpretation of data to yield damage level and/or location values not yet clearly possible.
6. Quantity of data required to make an accurate damage assessment is unknown.
7. Low cost transducer development is needed.
8. Very little understanding of damage/structure interaction.
9. Much information on this general topic is available in the literature but its usefulness is not clear.
10. Expense of hardware and software required for data acquisition and analysis is still high.
11. Desire to apply this technology to NDE of new materials before simple structures are understood.
12. Uniqueness of the predicted damage location and/or level values may be questionable.
13. Fixturing needed to insure reproduceable test conditions is unclear and may be extensive.

The problem of measurement noise is being addressed by Wicks and Mitchell [1,2,24], and their work seems to be bringing this problem under control. Concern over the available excitation methods is of less importance in the aerospace industry than in the other application areas mentioned earlier because of the control one has over the test article during the inspection process.

In the future, on the other hand, if this method is to be expanded to include in-service responses in the evaluation process as well, the information contained in these measurements will have to be examined very closely to insure that it will produce useful estimates of the integrity of

the structure. It is possible that the measurement sites selected for use in the modal test which would be done when the system is out of service may not provide the best possible information from the in-service measurements.

Another issue is the number of in-service measurement sites needed. This number will have a significant impact on not only the quality of the data but on the cost of the monitoring system as well. Therefore, it will be very important to select the measurement sites with great care and deliberation.

The need to develop low cost transducers stems from the desire to eventually be able to install the required instrumentation in the vehicle as a part of the construction process. In this way considerable effort and expense can be avoided during the service life of the vehicle by eliminating the need to install and remove large numbers of transducers each time a structural integrity assessment was to be made. At the same time, adequate instrumentation would still be available to permit a complete inspection to be performed.

Obviously, how this technology is applied by the general public and the cost of the data acquisition and analysis equipment are items which cannot be controlled. However, these are two issues which will play a significant role in the development and utility of this technology for NDE purposes.

The remainder of the items listed above will have to be addressed through comprehensive research efforts.

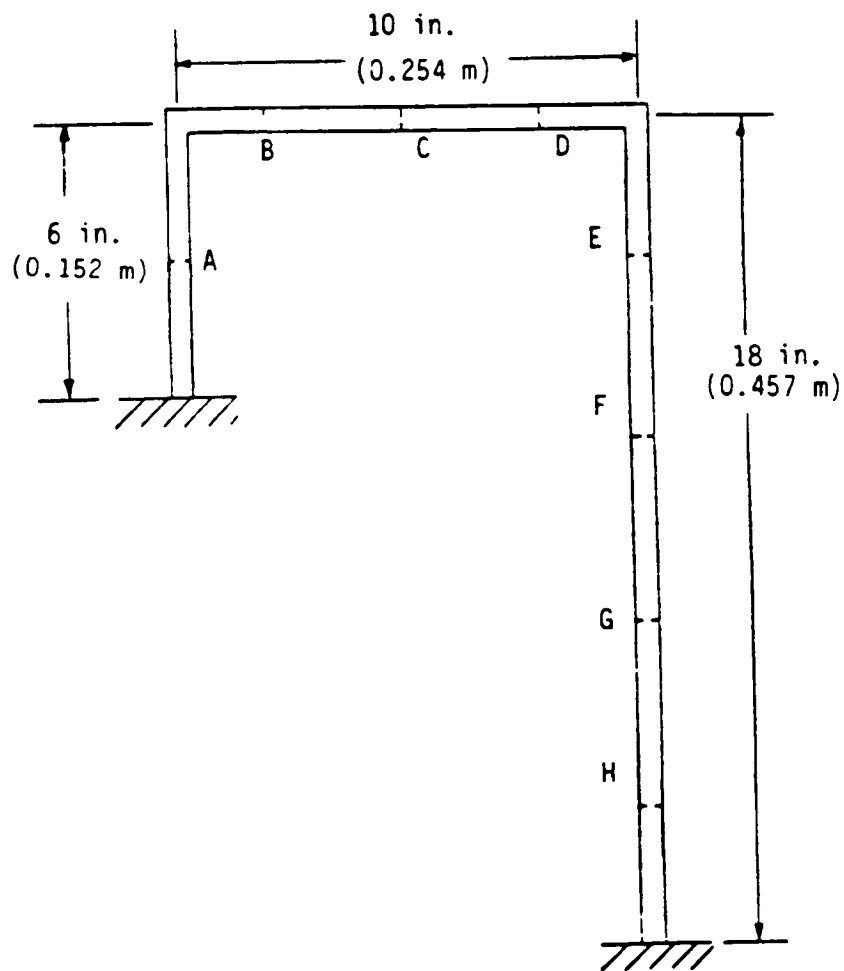
## CONCLUSIONS AND RECOMMENDATIONS

The ability of modal analysis methods to provide information which can be used for the NDE of structural systems is clear. However, many issues concerning the efficient and accurate utilization of this data for NDE purposes are unresolved. These include, but are not limited to, the amount of data needed, how accurate and repeatable the data must be, how this data should be processed and presented, and how the damage interacts with the dynamic characteristics of the structure. A comprehensive research effort will be required to successfully address these concerns.

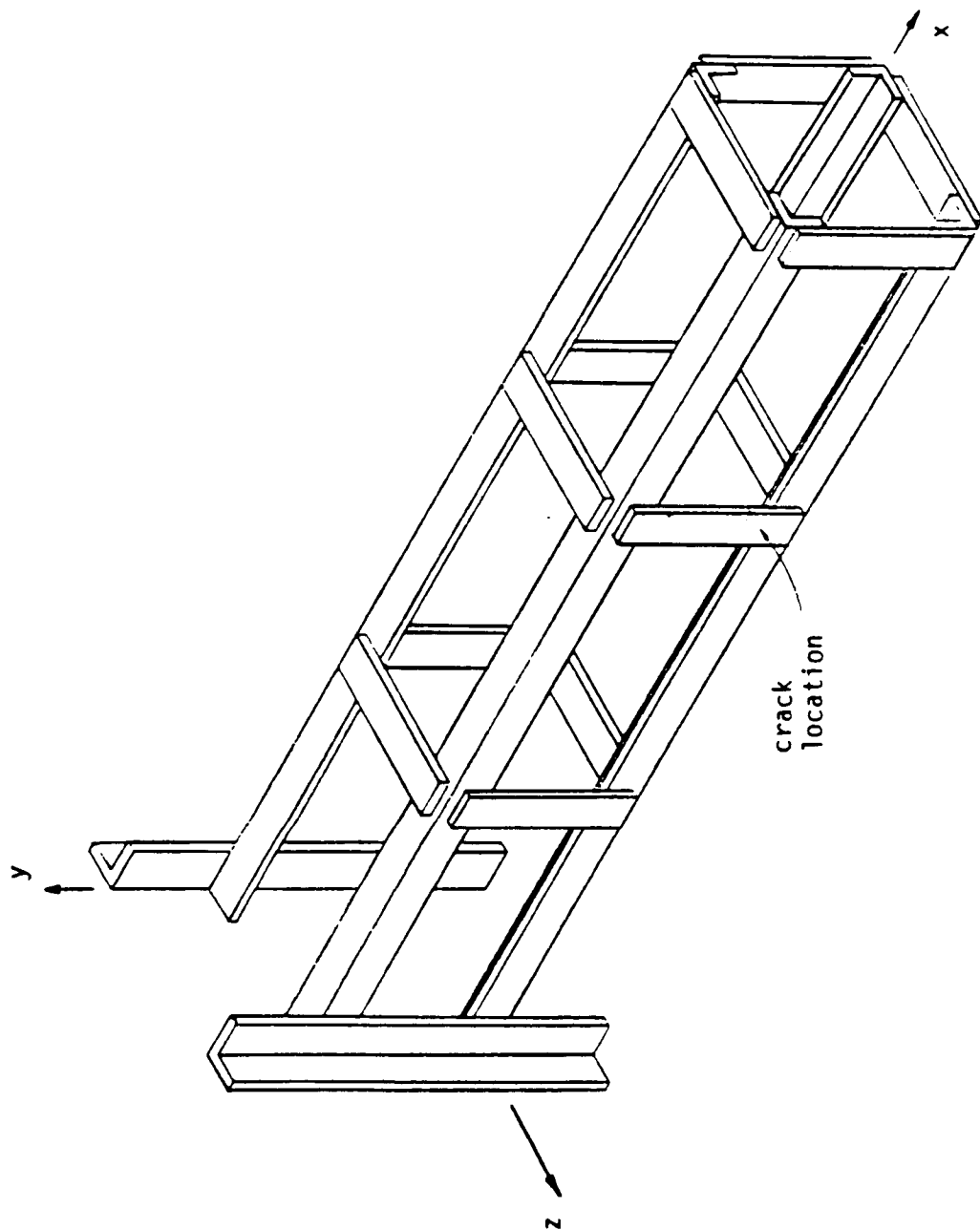
### Proposed Test Program

To familiarize the personnel of MSFC-ET53 with the application of modal analysis methods to NDE problems, the test program described below is proposed. This program takes advantage of existing test data and, thereby, provides a means of comparison so that any questions which may arise can be easily resolved.

1. Repeat the longitudinal and transverse beam experiments of Springer and Reznicek which used free-free samples. This will serve to illustrate the effects of temperature and mass loading on the measured data, and the difficulty of damage magnitude and location prediction on systems which can be solved analytically.
2. Repeat the tests carried out by Haisty and Duerr on unequal length U-frame structures. These test items featured fixed end conditions and will serve to demonstrate the application of the MAC for purposes of damage detection. Also, test data is available for comparative purposes and the structure is easily modeled using FEM methods.
3. Repeat the tests of Haisty and West on a box-beam structure. This structure is a three dimensional cantilever beam arrangement which was well documented in the earlier work. These test activities will demonstrate the effect of damage in both primary and secondary structural elements as well as the difficulties resulting from the use of typical mechanical fasteners. This structure is also easily modeled using FEM techniques.



U-frame Structure



Boxbeam Structure



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